TITLE: Bird Impact Analysis on a Bladed Disk

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ABSTRACT

A Smooth Particle Hydrodynamics (SPH) method has been developed to provide a transient structural analysis of fan blades during bird strikes [1], [3]
The bird is modeled by a set of lagrangian particles and a specific state of equation evaluates the pressure in the projectile. The SPH method has been coupled with the Finite Elements method by a contact algorithm and implemented in the fast dynamic code EUROPLEXUS [2], [4].

Unlike the classical Lagrangian formulations, this model avoids the severe distortions of projectile mesh during impact phase. An uniform bird slicing by the rotating blades is not assumed prior to the calculation. The method has been applied to compute the response and the residual deformations of a bladed disk.

1. INTRODUCTION

Bird strike in a turbofan engine is a phenomenon which can occur at each flight's stage and principally during take off and landing. These impacts generate severe loads on the fan stage and sometimes the strains undergone by the structure can lead to failure.

Prior to the final certification test, some expensive spin tests are usually performed to validate the initial design choices. A failure during a bird ingestion will be very expensive because of the necessary re-design of the blade (costs, delays). To reduce the number of these tests and to avoid any delay during the certification tests the manufacturers perform analyses with non-linear transient structural codes.
The task lies then in the development of a convenient and suitable industrial strategy to demonstrate the reliability of a Finite Element (FE) modelling to predict the impact loads and damage.
The classical Finite Elements method do not allow to treat completely this problem. The Lagrangian formulation is too tricky to handle for the bird because of large deformations. The coupled Euler-Lagrange method creates a significant numerical dissipation despite difficult remeshing in the case of rotating structures. Moreover, CPU time widely increases for these last calculations because a large area has to be meshed to anticipate fluid deformations and blades rotation. So, all these methods present major drawbacks to model bird the slicing by a rotating structure.

To avoid all this problems, SNECMA calculates bird strike with a SPH method. This formulation has been implemented in the fast dynamic analysis code EUROPLEXUS developed jointly by the French "Commissariat à l'Energie Atomique" and by the JRC of the European Community at ISPRA.

2. THE SPH METHOD

The SPH [5] method has been defined by astrophysicists during the 70's. But at the beginning of the 90's, some mechanical scientists have adapted this method to treat impact at very high velocities [6], [7], [8].
The SPH method is well-suited to simulate problems that present mesh distortions and large displacements.

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2.1. Mathematical principles

The discrete field f ,scalar or not, defined in a domain Ω can be approached and regularised by a field family $\langle f \rangle_h$, defined by :

$$\langle f \rangle_h = \int_\Omega f(y) \cdot W(x-y,h) \cdot dy \qquad (1)$$

with W Kernel or weight function

h smoothing parameter which determine the volume Ω_i around x where W takes its greatest values. This parameter h defines the regularity of $\langle f \rangle_h$

The field f can be the velocity, the density, the pressure …

The volume Ω_i is smaller than the domain Ω and the kernel W generally verify the following properties :

1. $W(x-y,h) > 0$ in Ω_i with $\Omega_i \subset \Omega$
2. $W(x-y,h) = 0 \quad \forall y \notin \Omega_i$
3. $\int_\Omega W(x-y,h) \cdot dy = 1$ (consistent condition)
4. $W(s,h)$ is monotonous and decreases with $s = \|x-y\|$
5. $W(s,h) \to \delta(s)$ with $h \to 0$ where $\delta(s)$ is the Dirac distribution

The most common kernels W are the Gauss, cubic or quadratic fonctions.

If the values of the field f are known for a finite number N of points x_i, the integral (1) can be approximated by a directe sum :

$$\langle f \rangle_h(\underline{x}) \cong \sum_{i=1}^{N} m_i \cdot \frac{f(\underline{x}_i)}{\rho(\underline{x}_i)} \cdot W(\underline{x}-\underline{x}_i,h) \qquad (2)$$

The mass m_i is associated to the particles $\underline{x}_i$ and the ratio $\frac{m_i}{\rho(\underline{x}_i)}$ represents the volume of the domain Ω_i connected to x_i.

The equation (2) looks like form functions in the finite element formulation.

The approximation of the field f can be easily applied to the fundamental equations of Mechanics. At the node number k :

- continuity equation :

$$\frac{d\rho(\underline{x}_k,t)}{dt} = \rho(\underline{x}_k,t) \cdot \sum_{i=1}^{N} \frac{m_i}{\rho(\underline{x}_i,t)} \cdot (v(\underline{x}_k,t) - v(\underline{x}_i,t)) \cdot \nabla_k W(|\underline{x}_k - \underline{x}_i|,h) \qquad (3)$$

- momentum equation :

$$\frac{d\langle \underline{v} \rangle(\underline{x}_k,t)}{dt} = -\sum_{i=1}^{N} m_i \cdot \left[\frac{\langle \underline{p} \rangle(\underline{x}_i,t)}{\langle \rho \rangle^2(\underline{x}_i,t)} + \frac{\langle \underline{p} \rangle(\underline{x}_k,t)}{\langle \rho \rangle^2(\underline{x}_k,t)} + \pi_{ij} \right] \cdot \nabla_k W(|\underline{x}_k - \underline{x}_i|,h) \qquad (4)$$

The pressure P is given by a state equation $\langle p \rangle(\underline{x}_i,t) = p(\langle \rho(\underline{x}_i,t) \rangle$ and π_{ij} is an artificial viscosity proposed by Monaghan and Gingold [9].

Two general remarks can be add to the presentation of the SPH method :

- The continuity equation avoids the boundary effects because the density evolves only when the distances between particles change.
- Corrections have to be introduced in this formulation to take into account the space and the time variations of the smoothing length. The time variations of h are described by the law of Benz [10] :

$$\frac{dh(\underline{x}_i,t)}{dt} = -\frac{1}{3} \cdot h(\underline{x}_i,t) \cdot \sum_{j=1}^{N} \frac{m_j}{\rho(\underline{x}_j,t)} \cdot (v(\underline{x}_i,t) - v(\underline{x}_j,t)) \cdot \nabla_k W(|\underline{x}_i - \underline{x}_j|,h) \qquad (5)$$

The space variations of h are obtained by the scatter approximation : $h(x,y)=\dfrac{h(x)+h(y)}{2}$.

This relation should be reintroduced in all the previous mechanical equations.

2.2. Application of the SPH method to the bird strike

The projectile is modeled by a set of Lagrangian particles arranged in a compact hexagonal system. Each particles is initially connected to twelve other particles but the connectivity is time dependant.

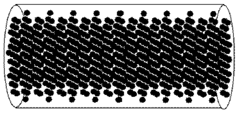

Figure 1 : projectile mesh

The mass of each particle is concentrated at the centre of the outer sphere. The bird material model is based on the studies of J. Willbeck [10]. He has developed a synthetic bird model which is composed of commercial gelatin and 10% of phenolic micro-balloons.
The state equation is based on the pressure-density relationship of each constituent. But to improve the calculation, this law distinguishes a shock and a reduction in pressure. This model gives very accurate loading including the Hugoniot peak and the stagnation pressure.

The SPH method used the cubic kernel with compact support [1], [11] :

$$W(r,h)=\frac{1}{\pi h^3}\begin{cases}\dfrac{3}{2}\cdot\left[\dfrac{2}{3}-\left(\dfrac{r}{h}\right)^2+\dfrac{1}{2}\cdot\left(\dfrac{r}{h}\right)^3\right] & 0\leq\dfrac{r}{h}\leq 1\\ \dfrac{1}{4}\cdot\left(2-\dfrac{r}{h}\right)^3 & 1\leq\dfrac{r}{h}\leq 2\\ 0 & \dfrac{r}{h}\geq 2\end{cases} \qquad (6)$$

The contact algorithm realize the coupling between SPH and the classical Finite Elements Methods. This interaction is treated as the shock of two spheres : one is a particle (bird) and the other is a factitious node representing the nodes of an element (blade).

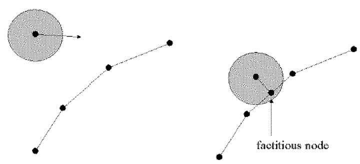

Figure 2 : contact detection

The global momentum is conserved in the normal direction whereas possible friction forces are not taken into account in the tangent direction [12] :

$$m_e\underline{\tilde{v}}_e+m_d\underline{\tilde{v}}_d=m_e\underline{v}_e+m_d\underline{v}_d \quad (7)$$

e particle
d defending node
tilde stands for ‘before impact’

The bird presents an hydrodynamics behaviour during impact, so the normal velocities after the shock are chosen equal (shock without rebound) :

$$\underline{v}_e=\underline{v}_d \quad (8)$$

These equations (7), (8) allow to calculate the velocity and the acceleration of the bird particles. This method gives accurate results only if the diameter of the particles and the size of the elements are equivalent.

3. INDUSTRIAL APPLICATION

Bird strikes are today currently simulated on civil fan using SPH method. The results for all kinds of blades (wide chord solid blades, hollow fan blades, shrouded blades …) are very close to experimental data [2],[4],[12].
This method has been applied to anticipate the mechanical behaviour of blades under different impact conditions than fan blades : the blades dimension and the rotation speed are different from fan civil applications. The nominal rotation speed is around 13.600 rpm and the seagull is fired with an axial velocity of 197 m/s.

To limit CPU time, only the impacted part of the rotor is represented. Each blade is meshed with shell elements and the disk with brick elements. The structural mesh approximately includes 33.000 degrees of freedom (cf. figure 3).

To compute accurately the bird slicing, the blades must be in motion in the global frame. A procedure was defined to describe the rotation of the impacted structure. This procedure follows three steps :

- calculation of the centrifugal stresses
- determination of the bird slicing
- deceleration of the rotor.

The first step is essential because the dynamic behaviour of the blades are widely influenced by this additional strength.
The boundary conditions must take into account the cyclic symmetry of the disk to model the effect of the rotor which is not meshed. The centrifugal forces are determined in the rotating frame. They are applied on every node and tend to expand the structure in the radial direction. Thus, it is necessary to impose the displacement continuity for each node of the lateral disk faces located at the same radial position (9).

$$\begin{aligned} v_{r1} &= v_{r2} \\ v_{\theta 1} &= v_{\theta 2} \end{aligned} \qquad (9)$$

v_r radial velocity

v_θ tangential velocity

(The mark 1 refers to one face and the mark 2 to the other face)

The calculation is conducted until the stresses are stabilised (the structure is damped on the first bending mode of a blade).
The bird impact appends on the global frame to represent correctly the slicing and the centrifugal stresses of the deformed structure. Numerically, the rotation is introduced by prescribed displacement on the nodes located on the lateral disk faces. The initial velocities is automatically determined by the code from the radial position of each node and from the rotation speed of the rotor.

The objective of this simulation is to anticipate the mechanical behaviour of the blades, so the outer shape of the projectile does not represent a real geometry of bird but a right circular cylinder (cf. figure 1).

The material behaviour of the blades is described by a dynamic elastic-plastic law. Contact conditions are imposed between each blade and the bird but also between blades to avoid penetrations under high bending moments.

The results are presented on a sector of three blades (figure 3-4). Snecma does not have test data to validate the computations, but the first results seem to predict realistic behaviour of blades. The deformation under impact is more severe than impact on a civil engine. During the bird slice, larger deflections occurred at the leading edge. The bird slice cut by each airfoil is not regular (even if the bird density is constant) because blades and projectile interact (figure 4).

No active element failure criteria is implemented in the code. The predicted maximum dynamic strain and its location indicate the possible cracking and material loss. The value of this criteria is determined with experimental data.

This simulation provide useful data to validate the design and the load definitions under impact. The global response of the structure under impact depends on the initial geometry and the simulation determines the mode which is excited (torsion or bending). For example, a torsional deflection can lead to peak strain response at the airfoil root region and failure.
Furthermore, the predicted response allow to validate the engine design. The computation provide information about the possible contact between the impacted blades and :

- the fan casing (radial deflection – figure 5)
- the following blades (tangential deflection – figure 6)
- the other compressor stage (axial deflection – figure 7)

4. CONCLUSIONS

The bird slicing is especially well-predicted without any assumption. The results confirm the major interest of the SPH method.

The calculations were not validated by experimental data but the global and local deformations seem to be well predicted : the blades interact with the bird and the results are coherent with the higher speed impact in such conditions.

The SPH method has demonstrated its ability to be used as an efficient analytical tool for predicting impact loads and damages due to bird ingestion. Since the analysis does not require important computer resource and CPU time, it can be used during the conception iterations and the qualification tests are performed on the final optimised geometry. The computations contribute to improve the quality of prediction of the dynamic behaviour of the blades under impact and therefore to increase the safety of flights.

ACKNOWLEDGEMENTS

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REFRENCES

[1] A. Letellier. Contribution à la modélisation d'oiseaux sur les aubes des réacteurs. PhD, Université d'Evry 1996

[2] A. Letellier, M. Berthillier, H. Bung and P. Galon. Bird impact on fan blade analysis using SPH method coupled with finite elements. Symposium on structures under extreme loading conditions. Orlando, 1997

[3] A. Legay, D. Leray. PLEXUS, introduction de la viscosité SPH. Rapport CEA, SEMT/DYN/RT/98.040/A, 1998

[4] P. Vignolles, P.X. Bussonet and J. Talbotec. Conception des aubes fan soumises à l'impact d'oiseaux. AGARD CP 1995

[5] W. Benz. Numerical modelling of non-linear stellar pulsation : problems and prospects. Kluwer Academic, Boston, MA, 269-288, 1990

[6] G.R. Johnson, R. Stryk. Dynamic three dimensional computations for solids with variable nodal connectivity. Int J for Num Methods (28),1989

[7] G.R. Johnson, E. Peteren, R. Strik. Incorporation of an SPH option into the EPIC code for a wide range of high velocity impact computations. Int J of Impact Engineering (14), 1993

[8] S.W. Attaway, M.W. Heinstein and J.W. Swegle. Coupling of smooth particle hydrodynamics with the finite element method. Nuclear Engineering and design (150), 199-205, 1994

[9] J.J. Monaghan, R.A. Gingold. Smoothed particle hydrodynamics : theory and applications to non-spherical stars, Montly Notices of the Royal Astronomical Society (181), 1997

[10] W. Benz. Smooth Particle Hydrodynamics : a review. Harvard-Smithsoniam Center for Astrophysics, 1989

[11] J. Wilbeck. Impact behaviour of low strength projectiles. Technical Report 77-134, Air Force Material Laboratory, Wrigth-Patterson Air Force Base, Ohio 45433, 1978

[12] J. Bonini, H. Bung. Structural Impact-Friction modelling in Explicit finite element code with the Lagrange Multiplier, 14th Conference on Structural Mechanics in Reactor Technology, vol. 6, 37-44, 1997.

Figure 3: Pre-stresses field in the bladed disk

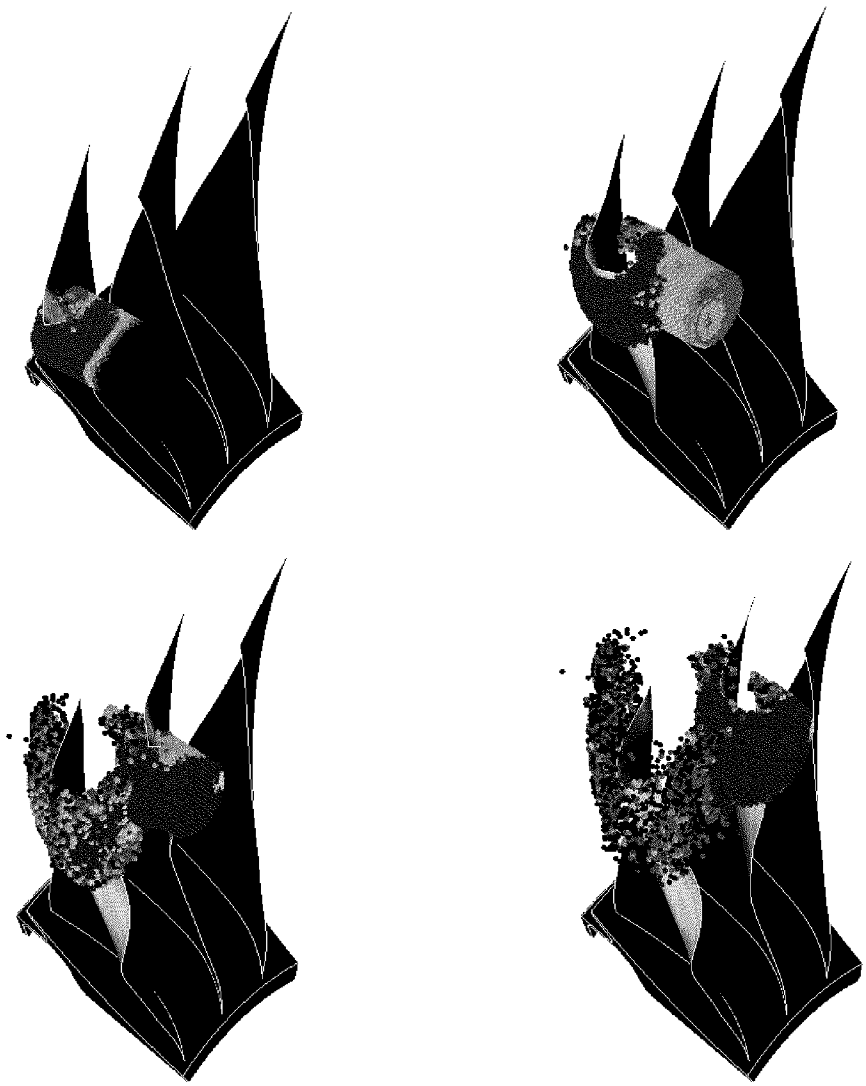

Figure 4 : bird slicing

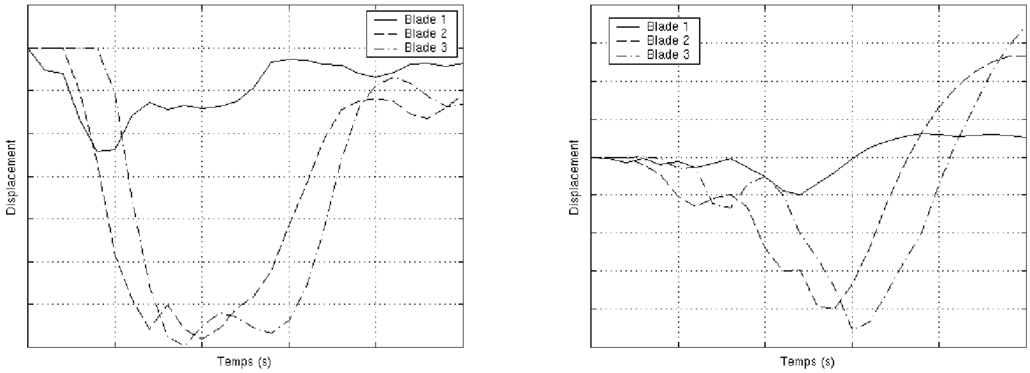

Figure 5: Blade tip leading and trailing edge radial deflection

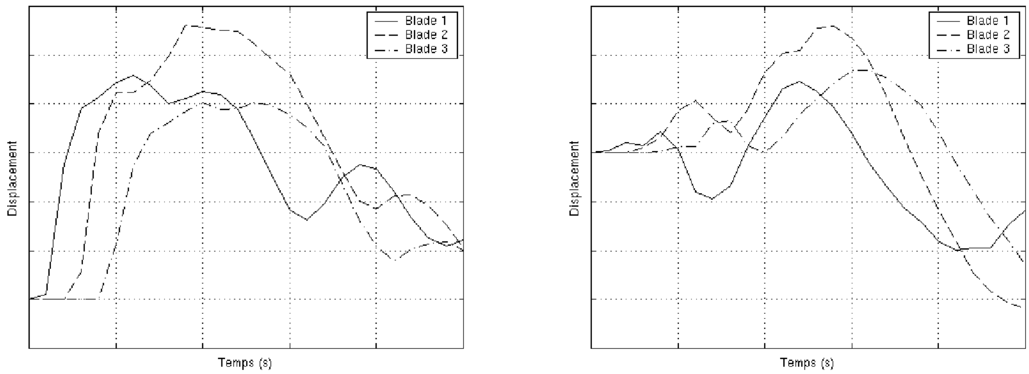

Figure 6: Blade tip leading and trailing edge tangential deflection

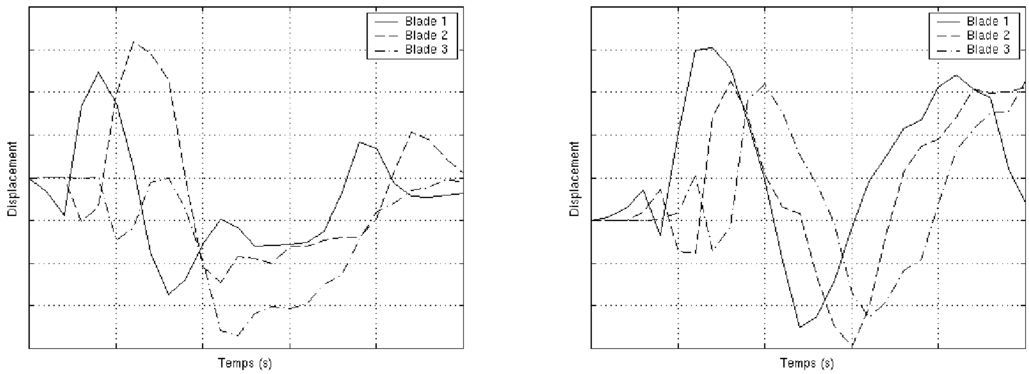

Figure 7: Blade tip leading and trailing edge axial deflection

Paper #31
Discussor's Name: Azzeddine Soulaimani
Author's Name: D. Chevrolet

Q: How do you apply the solid boundary conditions for the SPH method?

A: We are simply using conservation of the momentum at the boundary.